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PRESSURE MEASUREMENTS IN A LIQUID-FILLED CYLINDER AT HIGH CONING FREQUENCIES

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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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Endwall pressure measurements were completed in a liquid-filled cylinder for a Reynolds number near 193 and coning rates exceeding the spin rate. Previous mechanical and electrical systems were modified to accommodate coning rates as high as 20 Hz. Two fixed coning angles of 0.436 and 0.987 degree were used to examine nonlinear effects. Resulting pressure coefficient data (C_p) were verified to be linear with coning angle. The low Reynolds number experimental data were compared with a Spatial Eigenvalue Method that is applicable for this range of coning and spin frequencies. The theory predicted approximately 75 percent of the pressure magnitude that was actually measured.

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I. Introduction

Laboratory experiments have been conducted on forced coning gyroscopes to simulate the motion of spin-stabilized, liquid-filled projectiles [1,2,3,4]. However, these tests have always been for cases where the coning rate was slower than the spin rate. These experiments support theoretical analysis used to design payload configurations. During flight, pressures inside coning/rotating liquid-filled cavities can lead to destabilizing moments. The behavior of the liquid pressure is a strong function of the cylinder aspect ratio, the Reynolds number (Re), and the non-dimensional coning frequency (τ) denoted by:

$$Re = p\, a^2/\nu$$

$$\tau = f_1/p$$

where,	f_1	is the inertial coning rate
	p	is the inertial spin rate
	ν	is the fluid kinematic viscosity
	a	is the internal cylinder radius.

The present experiments have investigated a new region of interest that is applicable to a vehicle whose spin moment of inertia is larger than the transverse moment of inertia and whose flight can achieve a value of τ greater than 1. Further small-scale experiments in this unusual range of coning and spin frequencies are possible and support ongoing theoretical analysis of liquid payloads. Full-scale experiments of this type are possible on the Ballistic Flight Simulator.

Previous tests at high Reynolds numbers and low coning frequencies performed by Whiting verified linear theories and showed pressure coefficient response (C_p) plots corresponding to a resonance-type behavior (Ref 1). Nusca, D'Amico, and Beims (Ref 2) and later Hepner et al. (Ref 3) provided data for low Reynolds numbers and low coning rates. Under this condition, the behavior of C_p was relatively linear with the non-dimensional coning frequency (τ). Hepner also used a flight simulator to conduct experiments where phase differences between the liquid internal pressure and the coning motion were measured (Ref 4).

This report presents experimental data taken on a gyroscope where the coning rate exceeds the spinning rate ($\tau > 1$). This was accomplished by rebuilding the coning drive system and associated pressure circuits. Hence, lower spin rates (nominally 20 Hz) and faster coning frequencies produced the high ratio of coning to spin frequencies ($\tau > 1$). Data were taken for two endwall transducers at a single cylinder aspect ratio and Reynolds number. These experiments are intended to establish the experimental technique and to provide initial comparisons with available theories.

The Ballistic Research Laboratory has invested considerable effort in developing theoretical applications in the area of spinning/coning liquid payloads. Stewartson considered the stability of a liquid-filled top under very idealized conditions (Ref 5). D'Amico extended the original Stewartson tables of eigenvalues and residuals to coning frequencies greater than unity (Ref 6). Murphy examined the original Stewartson model and produced an improved linear theory (Ref 7) and further examined the case of unusual coning frequencies (Ref 8). Reference 8 showed that the liquid oscillations could not produce unstable flights where the non-dimensional coning frequency was greater than unity. Recent work by Hall, Sedney, and Gerber has produced a method that can treat low Reynolds numbers and unusual coning frequencies (Ref 9). Applicable theories are verified through laboratory simulation as more unusual or new payload concepts or flight vehicles evolve.

II. Experiment Description

The forced gyroscope apparatus used in References 1-3 has undergone several improvements. The belt and pulley system has been discarded for a direct drive motor with flywheel attachment (Figure 1). This direct drive system allows for higher coning frequencies approaching 20 Hz. Higher coning rates are possible by proper balancing of the coning apparatus. The adjustable angle cam was replaced with interchangeable fixed-angle coning plates. The plates allow the spindle to rest in a bearing encasement at a constant inclination angle ranging from 0 to 5 degrees (Figure 2).

The two-channel amplifier/filter circuit was modified to increase its gain at low frequencies for the present series of tests. The amplifier gain was roughly 843 for the inner

gage and 622 for the outer gage. A typical transfer function for the inner transducer of this circuit was taken and curve-fitted for easier data processing (Figure 3).

Silicon oil was used to completely fill the cylinder. At 25 °C the oil has a kinematic viscosity of 525 centistoke (cs) and a density of 0.968 gm/cc. For comparison, water has a kinematic viscosity of approximately 1 cs = $1 cm^2/s$ at standard temperature and pressure. The cylinder has an aspect ratio (half height to diameter) of 3.148 (Figure 4). The cylinder was filled and fitted with bearing spindles. The complete assembly was then dynamically balanced.

Internal pressures were measured for two coning angles: 0.463 and 0.987 deg. Large coning imbalance responses were present when a high coning angle plate was utilized. A motion sensor was positioned next to the apparatus to monitor vibration. Some reduction in the coning imbalance was accomplished through the addition of weights to the flywheel. The rotor spin was provided by another DC motor within the cage support. For these experiments a constant spin rate of 16 Hz produced a Reynolds number of 193. For a fixed coning angle and spin rate, the coning rate was varied to achieve a desired τ value. After an appropriate settling time, pressure magnitudes were noted and the coning rate was then changed. This process was continued to produce a sufficient survey range for τ and ensure the repeatability of the pressure data.

An instrumentation schematic is included as Figure 5 showing how the voltage outputs from the transducers (located at r/a=0.434, r/a=0.667) were amplified, filtered, and then transferred through the twelve channel slip ring. A 10 volt bipolar DC power supply was transferred to the rotating frame via the slip ring. A dynamic signal analyzer was used to find the peak amplitude of the pressure signal. Since the pressure transducers are located in the body-fixed frame, the pressure oscillations will appear at frequencies relative to the spin rate. In the previous experiments the desired pressure signal was located at a frequency equal to the spin rate minus the coning rate. The dynamic analyzer folds this negative frequency about 0 Hz so the response is observed at the value of coning rate minus the spin rate (f_1- p) as shown by the Fourier spectrum of Figure 6. All testing was conducted for prograde motion where the spinning and coning motions are in the same direction. References 3 and 4 contain retrograde pressure data for Reynolds numbers of 3.1 to 8 and Re=18,200 respectively.

III. Experimental Results

It was anticipated that the temperature of the liquid would increase due to viscous heating. This was observed and discussed in Reference 3. Since the Reynolds number depends upon the reciprocal of the liquid viscosity, changes in temperature will produce an error in Reynolds number. Temperature changes of only a few degrees were observed, changing the Reynolds number less than 4 %. As the liquid expanded in the cylinder, the absolute pressure steadily increased and the experimental run times were limited by the linear response pressure limit of the gages (Ref 3).

Table 1 shows the gyroscope system errors for the instrumentation and equipment used. The relevant formula to determine pressure coefficients is shown below:

$$C_p = P/(a\rho\, \alpha^2 p^2)$$

where, C_p is the non-dimensional pressure coefficient

P oscillating pressure magnitude

α is the coning angle

ρ is the fluid density

p is the inertial spin rate

a is the internal cylinder radius.

All data experiments started with a slow coning rate and increased to higher rates. The experiment was completed by performing the survey in reverse order. Tabulations of C_p versus τ were made for each gage position and for each angle (Tables 2,3). The experimental conditions and results are supplied for each set of transducer locations with error calculations included. The overall experimental error was due mostly to low pressure signals and a low spin rate. The inner gage had smaller error bars due to a higher gain that helped increase the signal levels. System errors also decreased for a coning angle of 0.987 degrees as the signal level

was increased. Error bars are omitted for clarity in Figures 7 and 8, but included in Figure 9 where it is seen that the data scatter is well within the error bounds.

Data from the same gage position for two coning angles can be coplotted to examine the linearity of the C_p data, as shown in Figure 8. Within the scatter of the data, a single trend was established for gage position r/a=0.667, thus verifying linear C_p behavior.

Experimental results of pressure coefficient data were compared to the theory in Figure 9. The Spatial Eigenvalue Method (Ref. 9) is applicable in this range of Reynolds number from 1 to 2000. This theory predicted approximately 75 percent of the pressure magnitude that was actually measured. An exact solution for the case when $\tau = 1$ is also included in Figure 9, and can be computed by the following formula

$$C_p = (r/a) * (c/a).$$

IV. Summary

A forced coning gyroscope device was modified to measure endwall pressures on a cylinder whose coning rate was faster than the spin rate. For the two different coning angles tested, pressure coefficient data were shown to be linear with respect to coning angle. The data were compared to the Spatial Eigenvalue Method. Measured and computed pressures differed by 25 %. This is unusually high, and explanations are not available.

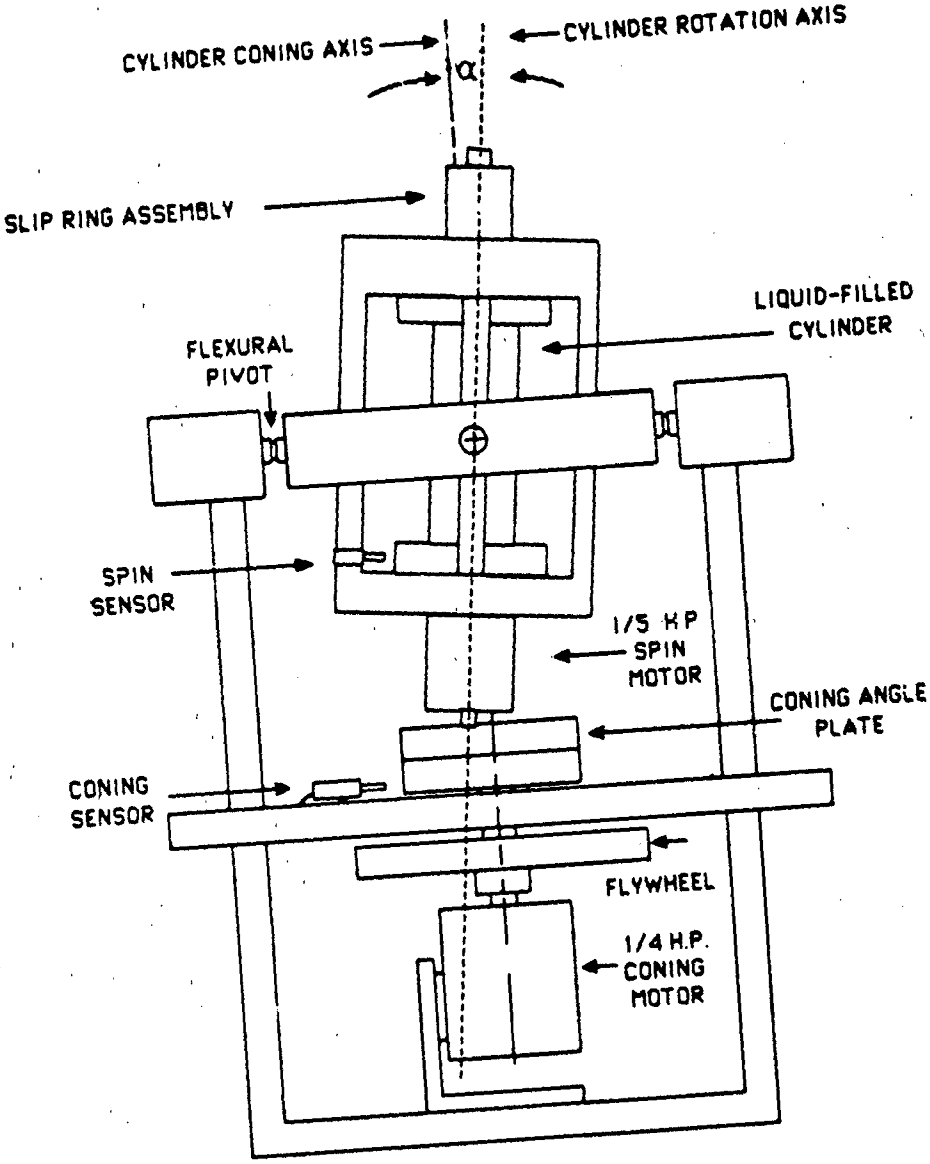

Figure 1. Forced precession gyroscope apparatus

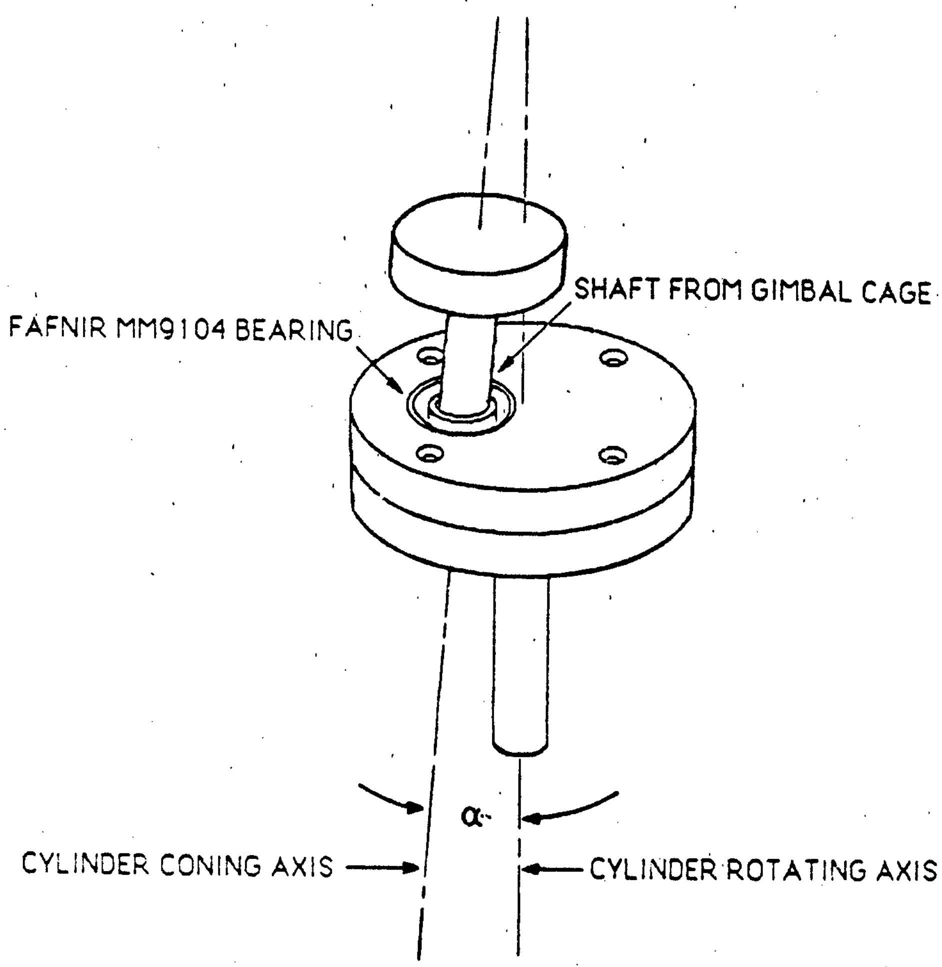

Figure 2. Predetermined coning angle plate.

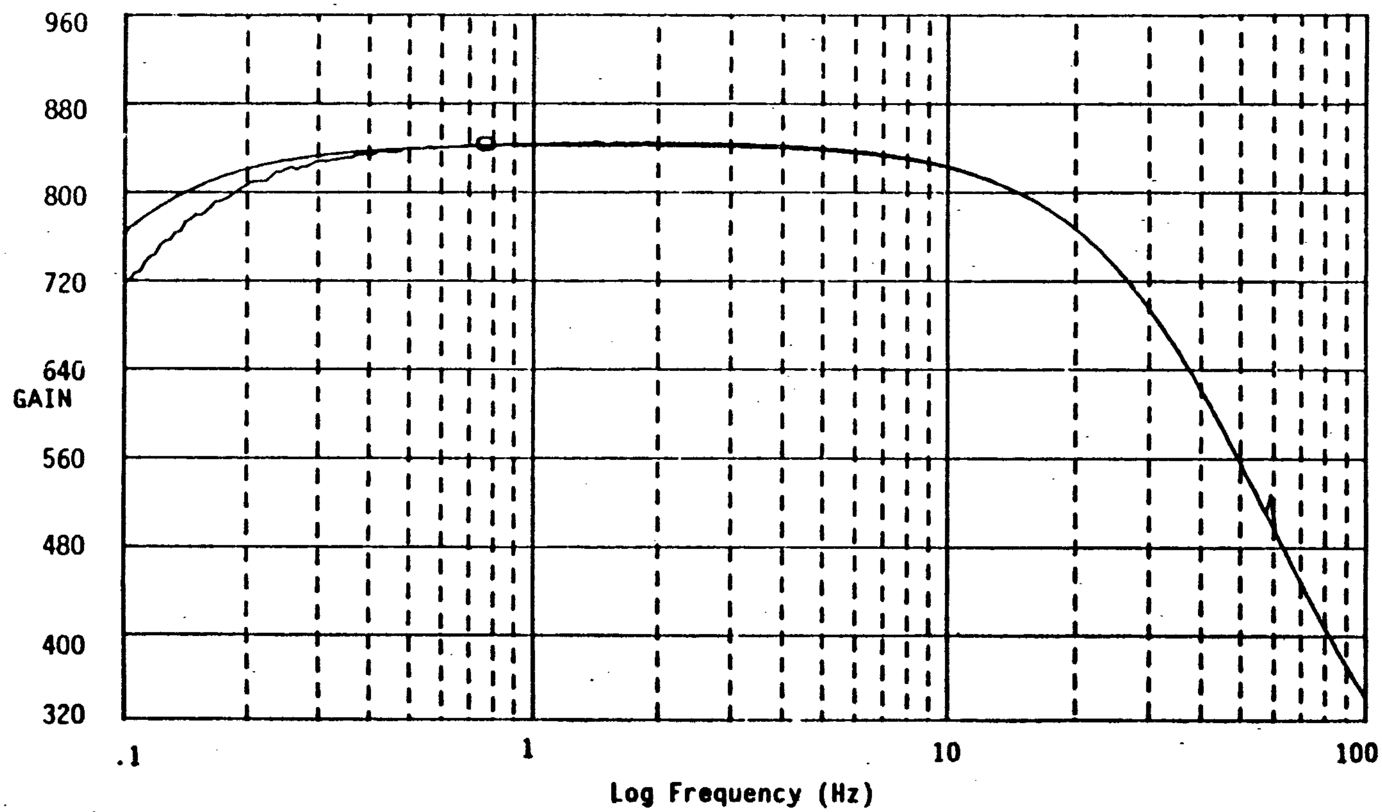

Figure 3. Transfer function of gage at r/a = 0.434.

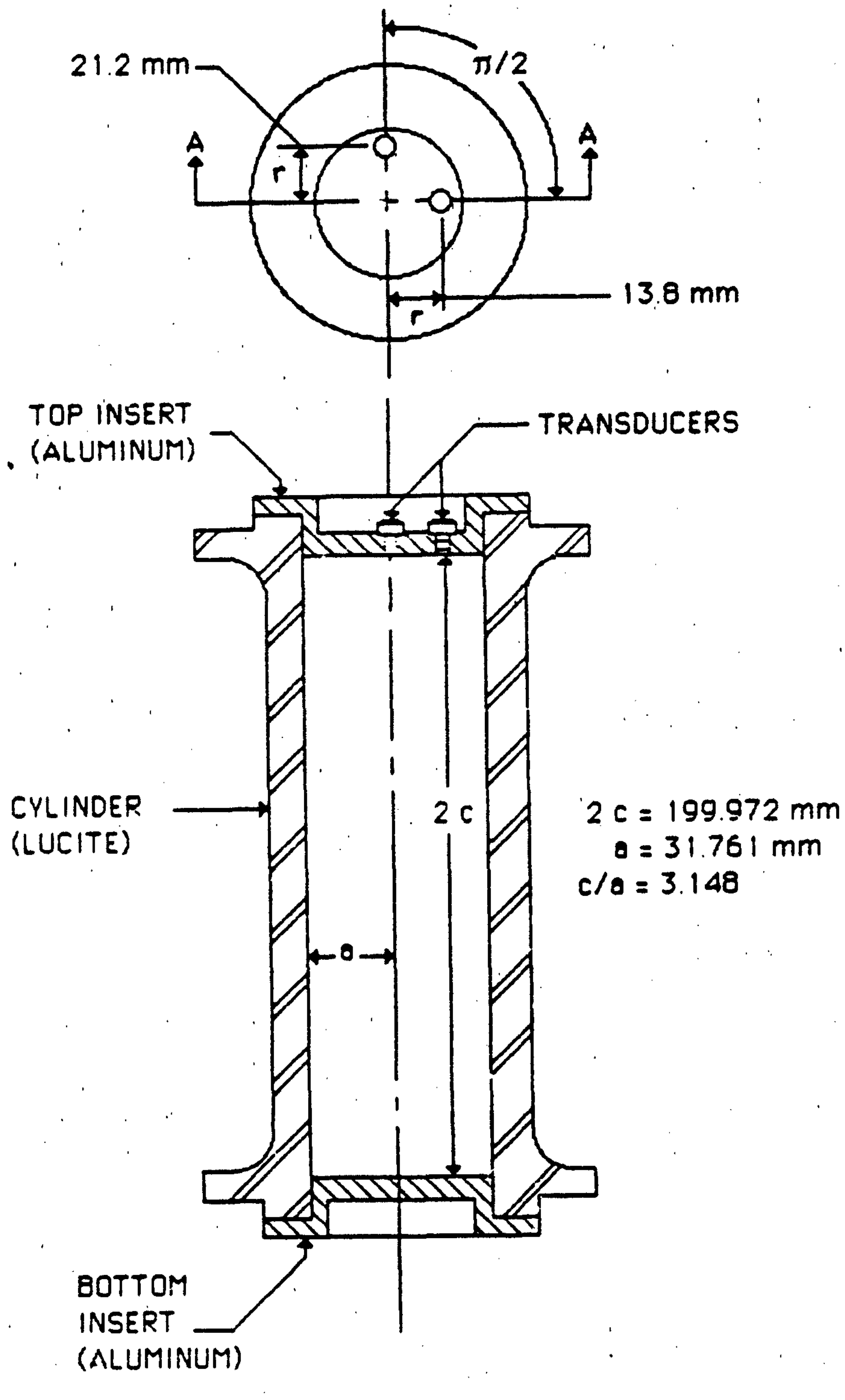

Figure 4. Cylinder dimensions and transducer locations.

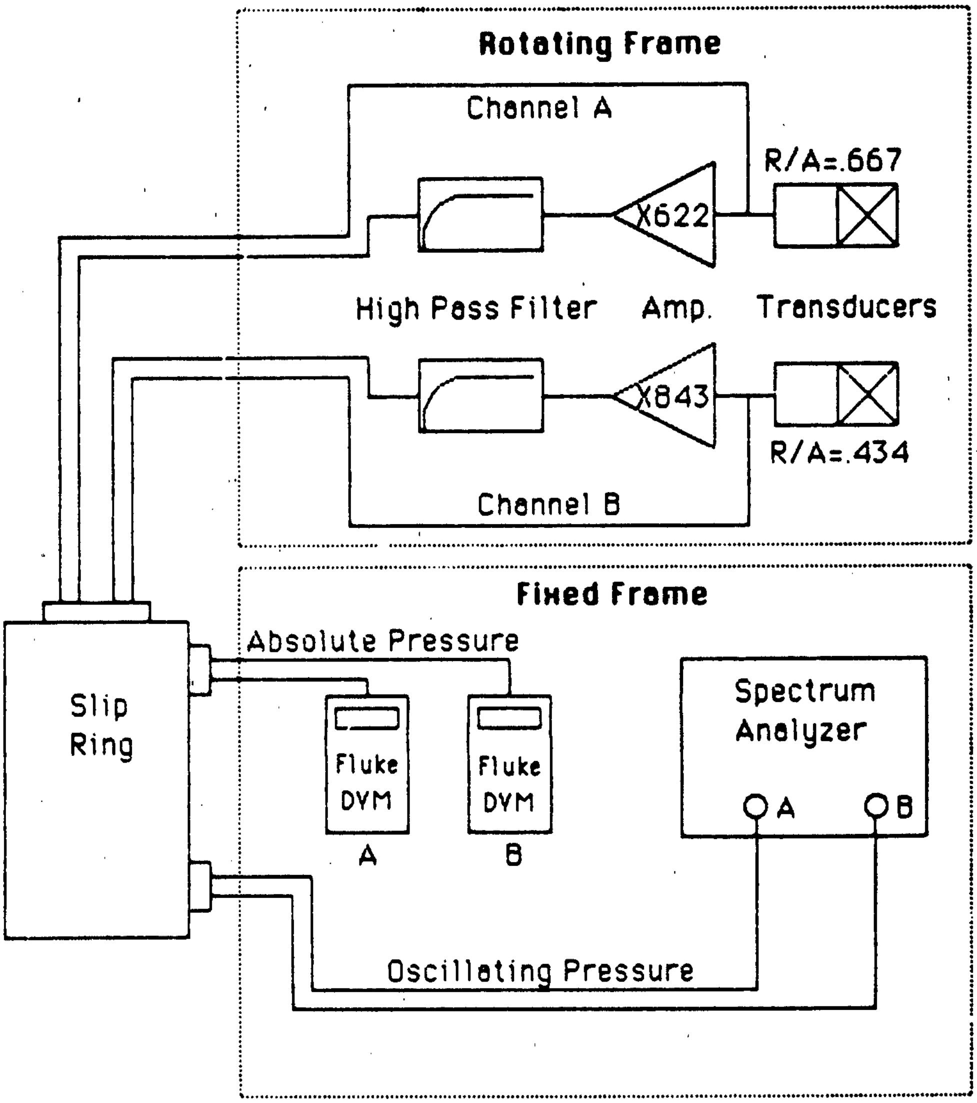

Figure 5. Instrumentation schematic.

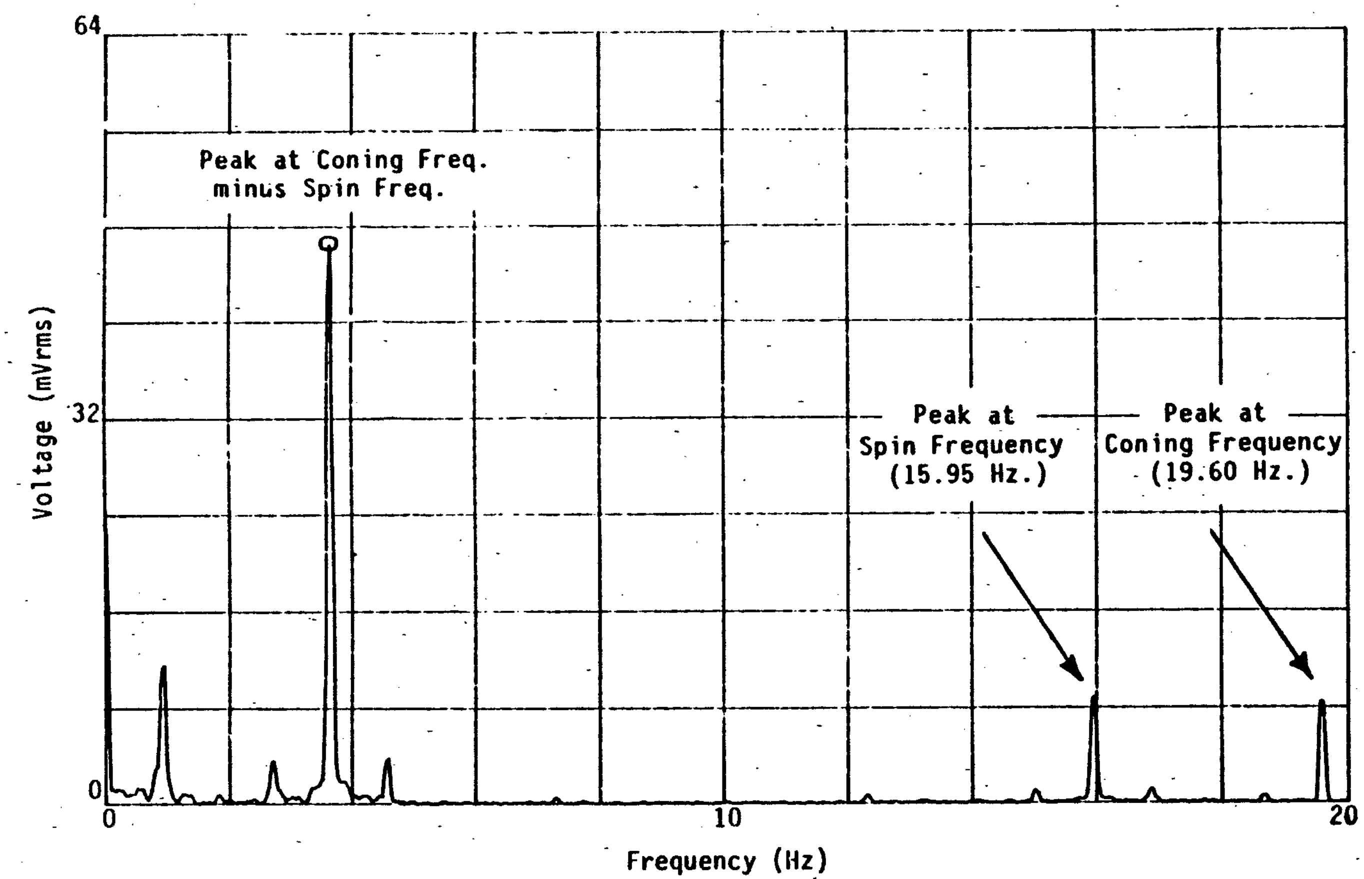

Figure 6. Sample spectrum of oscillatory pressure,
α = 0.987 deg., r/a = 0.434.

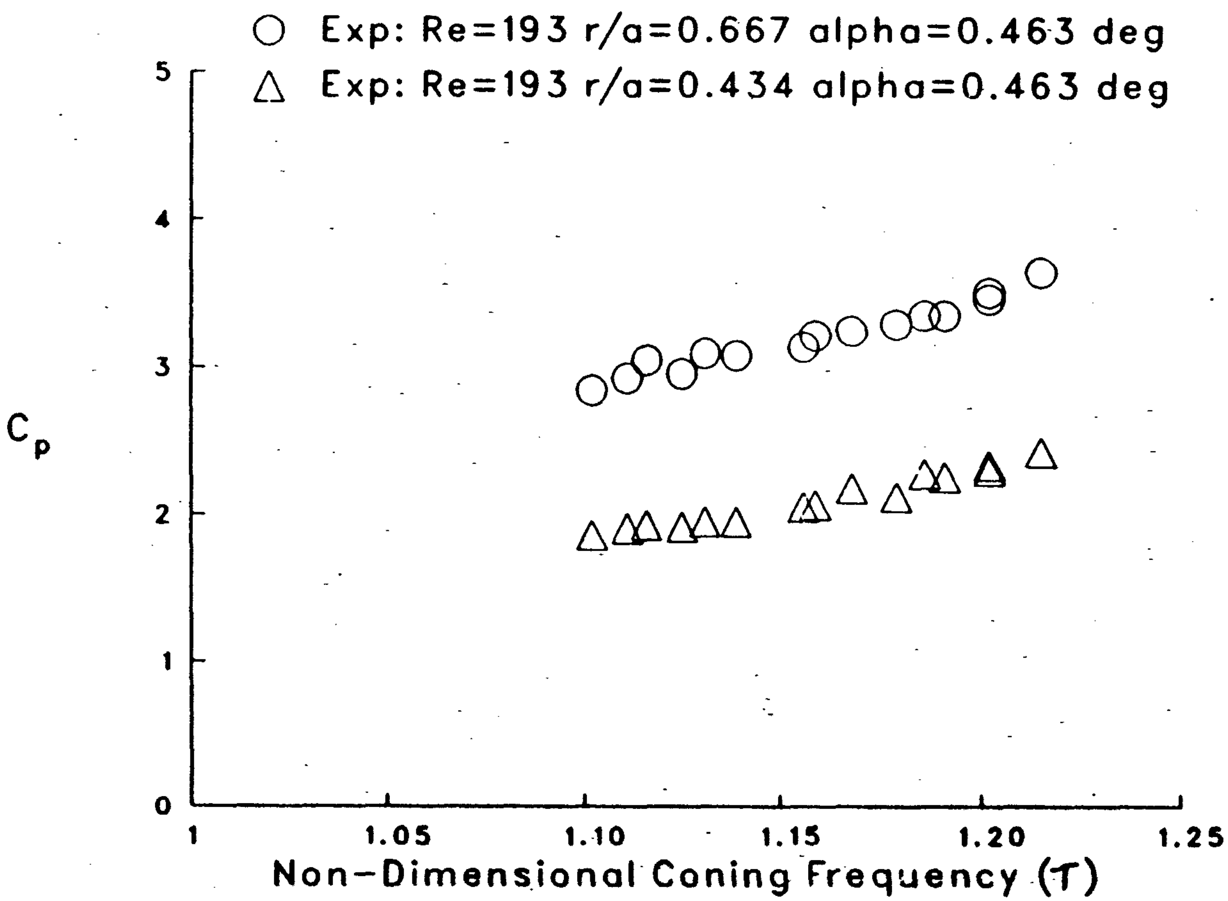

Figure 7. Pressure coefficient data for Re = 193, α = 0.463 deg., r/a = 0.434 and r/a= 0.667.

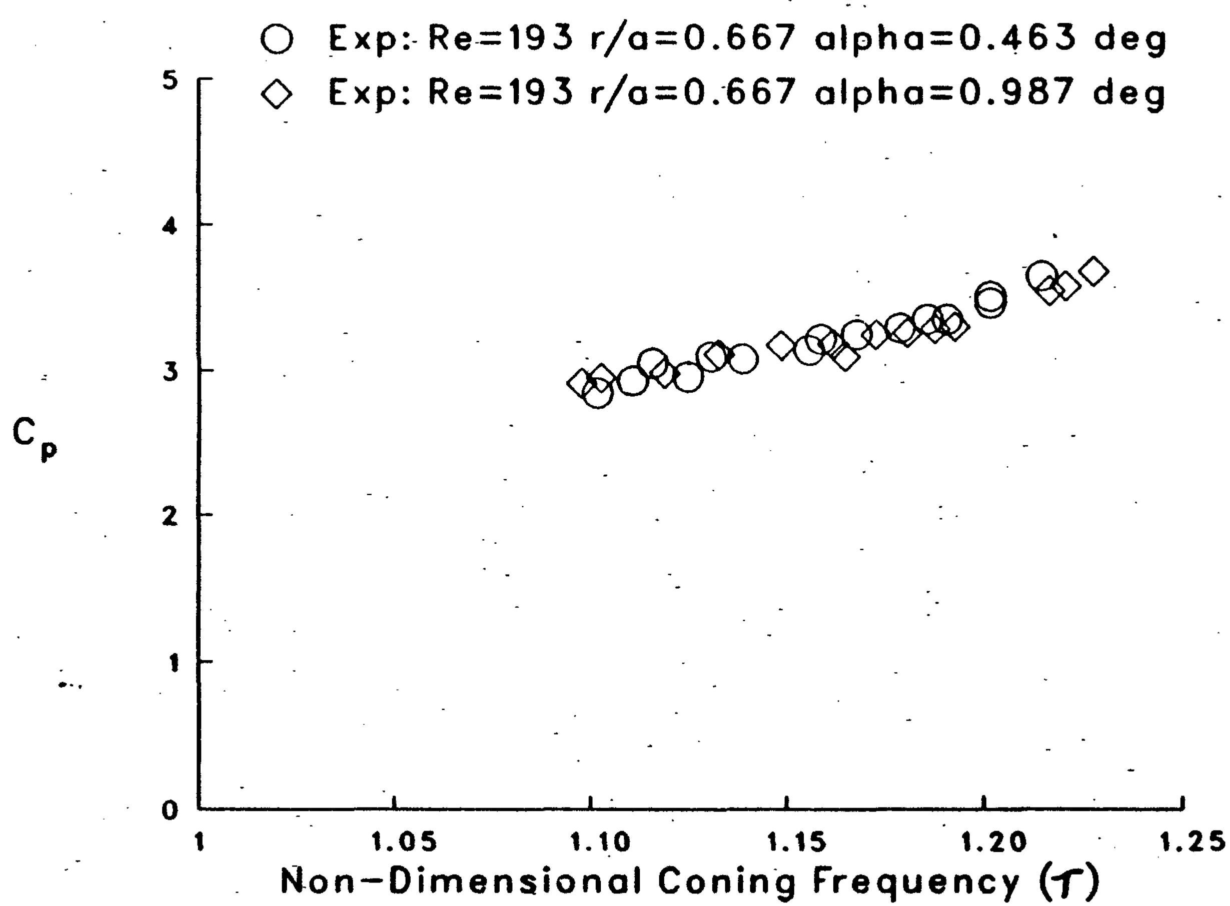

Figure 8. **Comparison of pressure coefficient data for linearity with coning angle for Re = 193, r/a = 0.667, α = 0.463 and 0.987 deg.**

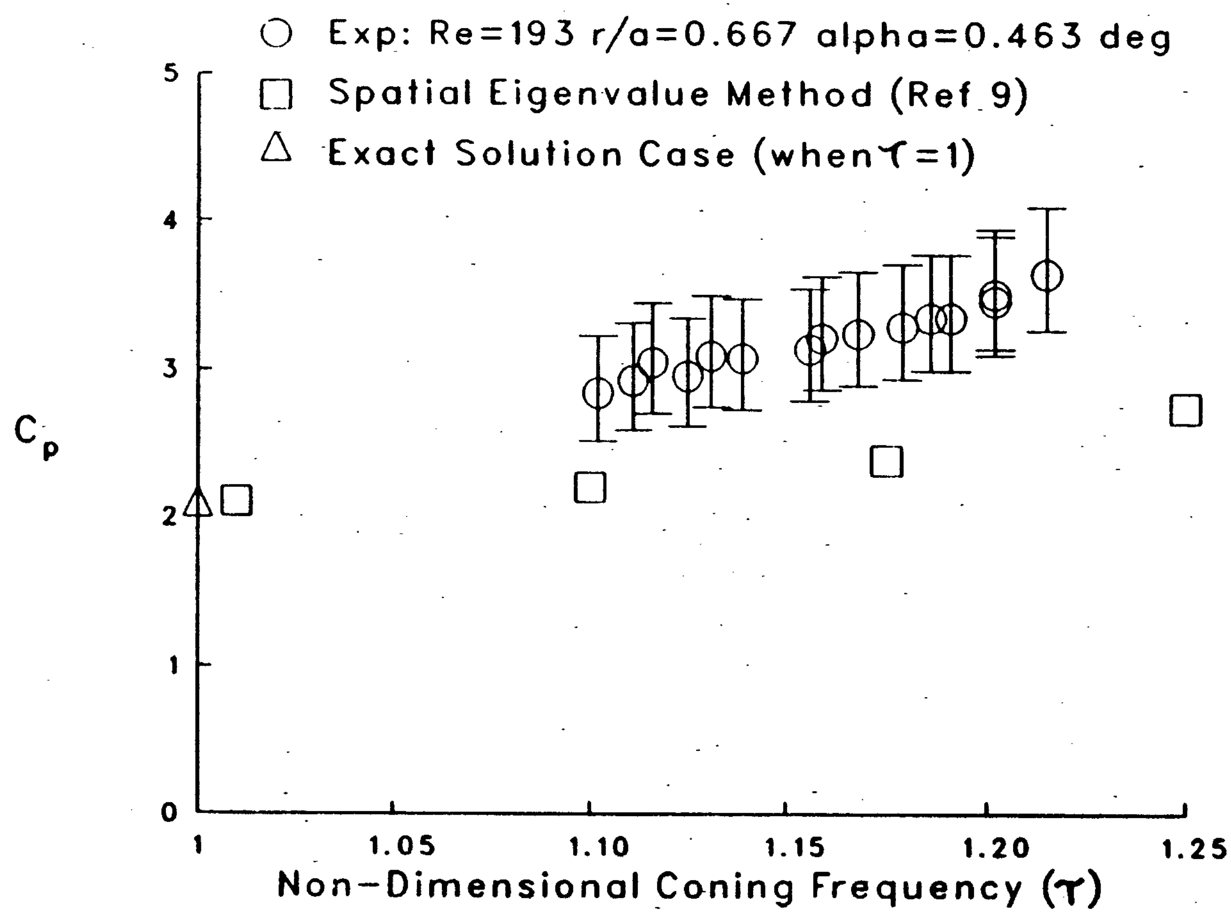

Figure 9. Comparison of Experimental Data to Spatial Eigenvalue Method and the Exact Solution Case when $\tau = 1$ at Re = 193 for pressure coefficients at $\alpha = 0.987$, $r/a = 0.667$.

Table 1: Gyroscope System Errors

Parameter	Range	Error
Mechanical Data:	- - - -	- - - -
Coning Rate	17.39-19.64 Hz	± 0.05 Hz
Spin Rate	16 Hz	± 0.25 Hz
Cylinder Radius	3.1761 cm	±0.0012 cm
Cylinder 1/2 Ht	9.9986 cm	± 0.0014 cm
Fluid Viscosity	540 cs	± 4.0 %
Fluid Density	0.968 g/cc	± 1%
Coning Angle	0.463° and 0.987°	± 0.002°
Transducer Data:	- - - -	- - - -
Pressure Signal	14.7-51.6 mV rms	± 1.0 mV rms
Pressure Calibration	(r/a = 0.434/r/a = 0.667)	- - - -
Slope	0.7798/0.7722 psia/mV	± 0.2%
Intercept	1.652/-1.184 psia	± 2.0 %
Signal Gain	843/622	± 2.0%

Table 2: Oscillatory pressure data for Re = 193.2, alpha = 0.463 deg., r/a = 0.667 and r/a = 0.434.

Run	Coning Rate (Hz)	Tau	Amplitude (V rms)	Signal Gain	Pressure (dyne/cm^2)	Minimum Cp	Cp	Maximum Cp
1	17.63	1.102	0.0188	623	2.27E+03	2.52	2.85	3.23
2	17.85	1.116	0.0201	622	2.43E+03	2.71	3.05	3.45
3	18.10	1.131	0.0204	622	2.47E+03	2.76	3.10	3.50
4	18.54	1.159	0.0212	622	2.57E+03	2.87	3.22	3.63
5	18.69	1.168	0.0214	622	2.59E+03	2.90	3.25	3.66
6	18.97	1.186	0.0221	622	2.67E+03	3.00	3.35	3.78
7	19.23	1.202	0.0231	621	2.80E+03	3.14	3.51	3.95
8	19.44	1.215	0.0240	621	2.91E+03	3.27	3.65	4.10
9	19.23	1.202	0.0228	621	2.76E+03	3.10	3.47	3.90
10	19.05	1.191	0.0221	622	2.67E+03	3.00	3.35	3.78
11	18.86	1.179	0.0217	622	2.63E+03	2.94	3.29	3.71
12	18.50	1.156	0.0207	622	2.51E+03	2.80	3.14	3.55
13	18.23	1.139	0.0203	622	2.46E+03	2.74	3.08	3.48
14	18.00	1.125	0.0195	622	2.36E+03	2.63	2.96	3.35
15	17.77	1.111	0.0193	622	2.34E+03	2.60	2.93	3.32

Spin Freq(Hz): 16.0 Aspect Ratio(c/a):3.148 Fill Ratio(%): 100 Re Num: 193.2
Radius(cm):3.176 Rad Position(r/a):0.667 Position (cm):2.120 Alpha(deg): 0.463
Gage ID Num: 33 Slope (psi/mV): 0.7722 Intercept(psi): -1.1838 Channel ID Num: 2
Room Temp(°C): 23.0 Viscosity(cs): 524.8 Density(g/cc):0.968 Cyl. Type: Lucite
Motion: Prograde Gage Excitation(V DC): 10.0

Run	Coning Rate (Hz)	Tau	Amplitude (V rms)	Signal Gain	Pressure (dyne/cm^2)	Minimum Cp	Cp	Maximum Cp
1	17.63	1.102	0.0165	844	1.49E+03	1.64	1.86	2.13
2	17.85	1.116	0.0171	844	1.54E+03	1.70	1.93	2.20
3	18.10	1.131	0.0173	844	1.56E+03	1.72	1.95	2.23
4	18.54	1.159	0.0183	843	1.65E+03	1.83	2.07	2.35
5	18.69	1.168	0.0193	843	1.74E+03	1.94	2.18	2.47
6	18.97	1.186	0.0202	843	1.82E+03	2.03	2.28	2.58
7	19.23	1.202	0.0207	842	1.87E+03	2.09	2.34	2.65
8	19.44	1.215	0.0215	842	1.94E+03	2.17	2.43	2.75
9	19.23	1.202	0.0204	842	1.84E+03	2.06	2.31	2.61
10	19.05	1.191	0.0200	843	1.80E+03	2.01	2.26	2.56
11	18.86	1.179	0.0188	843	1.70E+03	1.88	2.13	2.41
12	18.50	1.156	0.0182	843	1.64E+03	1.82	2.06	2.34
13	18.23	1.139	0.0173	844	1.56E+03	1.72	1.95	2.23
14	18.00	1.125	0.0170	844	1.53E+03	1.69	1.92	2.19
15	17.77	1.111	0.0169	844	1.52E+03	1.68	1.91	2.18

Spin Freq(Hz): 16.0 Aspect Ratio(c/a): 3.148 Fill Ratio(%): 100 Re Num: 193.2
Radius(cm): 3.176 Rad Position(r/a): 0.434 Position (cm): 1.380 Alpha(deg): 0.463
Gage ID Num: 32 Slope (psi/mV): 0.7798 Intercept(psi): 1.6518 Channel ID Num: 1
Room Temp(°C): 23.0 Viscosity(cs): 524.8 Density(g/cc): 0.968 Cyl. Type: Lucite
Motion: Prograde Gage Excitation(V DC): 10.0

Table 3: Oscillatory pressure data for Re = 193.2, alpha = 0.987 deg., r/a = 0.667 and r/a = 0.434.

Run	Coning Rate (Hz)	Tau	Amplitude (V rms)	Signal Gain	Pressure (dyne/cm^2)	Minimum Cp	Cp	Maximum Cp
1	17.56	1.098	0.0410	623	4.95E+03	2.66	2.91	3.19
2	17.90	1.119	0.0419	622	5.07E+03	2.61	2.98	3.26
3	18.64	1.165	0.0435	622	5.27E+03	2.83	3.10	3.39
4	19.08	1.193	0.0464	622	5.62E+03	3.02	3.30	3.61
5	19.47	1.217	0.0502	621	6.09E+03	3.28	3.58	3.90
6	19.64	1.228	0.0516	621	6.26E+03	3.37	3.68	4.01
7	19.00	1.188	0.0462	622	5.59E+03	3.01	3.29	3.59
8	18.77	1.173	0.0456	622	5.52E+03	2.97	3.25	3.55
9	18.38	1.149	0.0446	622	5.40E+03	2.90	3.18	3.47
10	17.65	1.103	0.0415	623	5.02E+03	2.69	2.95	3.23
11	18.13	1.133	0.0437	622	5.29E+03	2.84	3.11	3.40
12	18.59	1.162	0.0447	622	5.41E+03	2.91	3.18	3.48
13	18.90	1.181	0.0458	622	5.54E+03	2.98	3.26	3.56
14	19.53	1.221	0.0502	621	6.09E+03	3.28	3.58	3.90

Spin Freq(Hz): 16.0	Aspect Ratio(c/a):3.148	Fill Ratio(%): 100	Re Num: 193.2
Radius(cm):3.176	Rad Position(r/a):0.667	Position (cm):2.120	Alpha(deg): 0.987
Gage ID Num: 33	Slope (psi/mV): 0.7722	Intercept(psi): -1.1838	Channel ID Num:2
Room Temp(°C): 23.0	Viscosity(cs): 524.8	Density(g/cc):0.968	Cyl. Type: Lucite
Motion: Prograde	Gage Excitation(V DC): 10.0		

Run	Coning Rate (Hz)	Tau	Amplitude (V rms)	Signal Gain	Pressure (dyne/cm^2)	Minimum Cp	Cp	Maximum Cp
1	17.56	1.098	0.0320	844	2.88E+03	1.53	1.70	1.87
2	17.90	1.119	0.0356	844	3.21E+03	1.71	1.89	2.07
3	18.64	1.165	0.0384	843	3.46E+03	1.85	2.04	2.23
4	19.08	1.193	0.0425	843	3.83E+03	2.06	2.25	2.47
5	19.47	1.217	0.0444	842	4.01E+03	2.15	2.36	2.58
6	19.64	1.228	0.0460	842	4.15E+03	2.23	2.44	2.67
7	19.00	1.188	0.0402	843	3.63E+03	1.94	2.13	2.34
8	18.77	1.173	0.0382	843	3.45E+03	1.84	2.03	2.22
9	18.38	1.149	0.0358	843	3.23E+03	1.72	1.90	2.09
10	17.65	1.103	0.0318	844	2.86E+03	1.52	1.68	1.86
11	18.13	1.133	0.0337	844	3.04E+03	1.62	1.79	1.96
12	18.59	1.162	0.0358	843	3.23E+03	1.72	1.90	2.09
13	18.90	1.181	0.0[illegible]9	843	3.33E+03	1.78	1.96	2.15
14	19.53	1.221	0.0428	842	3.86E+03	2.07	2.27	2.49

Spin Freq(Hz): 16.0	Aspect Ratio(c/a): 3.148	Fill Ratio(%): 100	Re Num: 193.2
Radius(cm): 3.176	Rad Position(r/a): 0.434	Position (cm): 1.380	Alpha(deg): 0.987
Gage ID Num: 32	Slope (psi/mV): 0.7798	Intercept(psi): 1.6518	Channel ID Num:1
Room Temp(°C): 23.0	Viscosity(cs): 524.8	Density(g/cc): 0.968	Cyl. Type: Lucite
Motion: Prograde	Gage Excitation(V DC): 10.0		

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List of Symbols

a	internal cylinder radius
c	half height of cylinder
C_p	nondimensional pressure coefficient
f	fill ratio of cylinder
l	internal length of cylinder ($l=2c$)
p	inertial spin rate of cylinder
P	oscillating pressure magnitude
Re	Reynolds number $= pa^2/n$
r	radial position
α	cylinder coning angle
ρ	fluid density
ϕ_1	cylinder inertial coning rate
τ	ratio of coning rate to spin rate
ν	fluid kinematic viscosity

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